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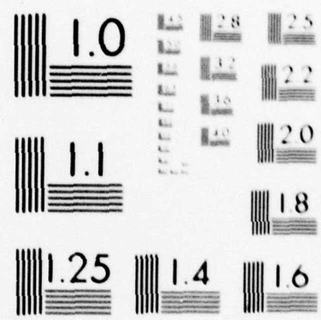
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CONSTRUCTION AND PROPERTIES OF A CARBON FIBRE REINFORCED ALUMINIUM BUS BAR FOR A CONTACTLESS POWER TRANSFER SYSTEM

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ABSTRACT

The production and properties of 7 m long carbon fibre reinforced aluminium alloy hybrid beams are described. The beams have been successfully used for some months as bus bars for contactless power supply to an induction motor drive and hoist system. In some cases limited buckling and delamination, which could be easily repaired, were observed in the reinforcement and between the metal and composite. The causes of this behaviour are discussed.

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ILLUSTRATIONS

1. Introduction

The work described involved the construction and measurement of the properties of aluminium bus bars reinforced with carbon fibre composite. A pair of bars approximately 7 m in length and supported at either end were required to span an isolated working compartment or cell. The 2 reinforced aluminium bars serve as sections of single turn primary windings passing through the window areas of the two transformer cores (Scott connection). A travel carriage driven by an induction motor was suspended from a steel gantry above the cell and from this travel carriage was hung a 500 kg hoist operated by another induction motor. To avoid fatigue problems it was necessary that the deflection in the bus bars due to their own weight was minimal so that the motor could move freely over their complete length without mechanically loading the bars. Either bar carried a maximum current of approximately 1500 amps and was subject to temperature changes of up to $70^{o}C$.

By using an inductively coupled system to supply the drive and hoist motors the travel carriage and hoist systems were reduced to two basic components, viz transformer and induction motors, thereby achieving minimum maintenance inside an active area and removing the disadvantages of brush/slip ring contacts together with trailing cable feeds. Operational commands to the travel carriage and hoist were also transmitted via the bus bars.

2. Experimental Work

The geometry and size of the aluminium section was limited, by the design of the transformer cores to a cross section 50 mm high × 12 mm wide with a maximum total thickness of carbon fibre composite, across the width, of 6 mm. The overall length was 7 m. The aluminium alloy specified was BS 1474/NE8/M which contained 4.5% magnesium and had not been heat treated. Immediately prior to the application of the reinforcement the aluminium was etched in a solution of 7½% by weight sodium bichromate and 15% by volume H_2SO_4, made up with distilled water, for 30 minutes at $60^{o}C$.

To obtain maximum stiffness a very high modulus carbon fibre, Celanese GY70, was used together with a liquid bisphenol A epoxide (Ciba Geigy MY750) modified with 10% of Du Pont's urethane L100 to achieve the optimum adhesion between the components. Both components were cured with DDS. The cure schedule was overnight at $120^{o}C$ or 2 hours at $150^{o}C$. To eliminate bowing in the reinforced beam the composite was distributed equally about the neutral axis.

Initially two model sections about 1.3 m long were produced. The first of these showed that it was difficult to handle the carbon fibre and resin while keeping the fibres straight and while clamping to consolidate the composite. For the second short bar, and the 7 m long units, it was decided to use lengths of pultruded, B staged, fibre composite to apply to the top and bottom of the aluminium. Steel plates were used to contain the prepreg, pressure applied with a series of clamps and curing effected by winding the whole assembly with heating tape. In this way an even composite layer containing about 35% by volume of fibre could be applied to the alloy bar.

The flexural modulus of one of the shorter reinforced bars (with the composite on the top and bottom) was determined, from a 3 point bending test, to be 84.9 GPa. Measurements were repeated with the bar at 100°C and, at room temperature, after 10 cycles between room temperature and 100°C. The results were 77.1 GPa and 85.3 GPa respectively. Care was taken with the measurements to allow for bedding in of the supports and weight of the specimen. No measurements were made with the bar supported such that the composite was on either side, though the reinforcement would also provide stiffening in this case.

Delamination between the composite and metal occurred over a length of several cms at the end of one of the shorter bars. With the 7 m long sections repeated compression failure, sometimes accompanied by localised delamination, was observed in certain parts of the carbon fibre composite sections when the reinforced bar cooled down. An example is shown in Figure 1. The breaks, which were between 65 and 85 mm apart were repaired by carefully cutting through the failure zone, sticking the delaminated material to the metal with a room temperature curing epoxide and filling the gap caused by the cut with a similar epoxide filled with 60% by volume of 10 μm glass beads. 7 m long bars repaired in this way have proved successful in service over a period of several months with no further signs of damage.

Sections of composite were removed from one of the bars and the mechanical properties measured in flexure. The modulus was 163 GPa, flexural strength 401 ± 50 MPa, and interlaminar shear strength 24.3 ± 2.1 MPa. The average fibre volume loading was 35.0% by volume.

3. Discussion

3.1 Deflection of the Beam

Using a strength of materials approach it can be shown that for the section of bar illustrated in Figure 2, the modulus of the hybrid beam, E_H, in terms of the moduli of the carbon fibre composite, E_C, and aluminium alloy, E_A, is given by

$$E_H = E_C\left(1 - \frac{h^3}{d^3}\right) + \frac{h^3}{d^3} E_A \qquad (1)$$

where h and d are defined in Figure 2.

If the section is rotated through 90°, in the plane of paper, we have

$$E_H = \left(1 - \frac{h}{d}\right) E_C + \frac{h}{d} E_A \qquad (2)$$

The measured flexural modulus of the aluminium was 67 GPa. Using this figure and taking E_C = 163 GPa at room temperature and 151 GPa at 100°C (see 1) the modulus of the hybrid beam, from equation (1), is 94.7 GPa at room temperature and 91.2 GPa at 100°C, values with which measured properties compare favourably. Thermal cycling had no significant effect on the room temperature modulus indicating that there was no degradation of the composite/metal bond.

In use, when spanning the cell, the reinforcement of the hybrid beam is at the top and bottom. The extra lateral stiffening of the beam, compared to an all metal

one, is, from equation (2), about 15% - a useful bonus.

The maximum mid-point deflection, δ_{max}, of a simply supported beam under its own weight, $W(Nm^{-1})$, is given by

$$\delta_{max} = \frac{5W\,l^4}{384\,EI} \qquad (3)$$

where l is the span, and $I = \frac{1}{12} bd^3$, with b and d having their previous meaning. For an aluminium alloy beam 50 mm high × 12 mm wide, and 7 m in length, using the measured value of E_A, equation (3) gives a maximum mid-point deflection of 59 mm. A similar beam with 3 mm of carbon fibre composite on the top and bottom has a δ_{max} at room temperature of 35.6 mm and at 100°C of 39.2 mm, a very considerable improvement compared with an unreinforced bar. Since the overall dimensions of the reinforced beam and cross section of the metal were limited by the geometry of the transformer cores and current requirements of the induction motors there was no possibility of a further reduction in δ_{max}.

3.2 Compression Cracking

To account for the multiple compression failure of the composite and delamination which occurred in one specimen consider the carbon fibre composite/aluminium hybrid as a macrocomposite, made from two carbon fibre resin composite 'fibres' and an aluminium alloy 'matrix'. At the curing temperature both components may be assumed to be free of internal stresses, but as the hybrid cools the carbon fibre composite having a coefficient of expansion, α, of approximately $-1 \times 10^{-6}\ {}^{o}C^{-1}$ will be put into compression and the alloy with a coefficient of expansion, α_A, of about $22 \times 10^{-6}\ {}^{o}C^{-1}$, into tension. If σ_A, A_A, σ_C and A_C are the stresses and cross sectional areas for the two components then a force balance gives:

$$\sigma_A A_A + \sigma_C A_C = 0 \qquad (4)$$

while equating the strains per unit length gives:

$$\frac{\sigma_A}{E_A} - \frac{\sigma_C}{E_C} = (\alpha_A - \alpha_C)\,\Delta T \qquad (5)$$

where ΔT is the temperature change.

Taking the area of the aluminium as 50 × 12 mm^2 and of the composite as 6 × 12 mm^2, equation (4) gives $\sigma_A = -0.12\,\sigma_C$. Substituting for σ_A in equation (5), taking $\Delta T = 130^oC$ and using measured values of E_A and E_C gives a compressive stress in the composite of 377 MPa. The flexural strength of the composite reinforcement was 401 ± 50 MPa so it is likely that compression failure will occur sometimes in the reinforcement.

We can calculate the distance between successive failure planes as follows. When a compression failure occurs in the composite, stress is transferred by shear back into the composite until the stress is again sufficient to cause failure. If

the distance between failure planes lies between x and 2x and τ is the fibre composite/metal shear strength, then, remembering that there are two composite strips of width b,

$$A_C \sigma_C = 2bx\,\tau \tag{6}$$

or

$$x = \frac{A_C \sigma_C}{2b\,\tau}$$

Taking σ_C = 401 MPa and τ = 24.3 MPa as a minimum value, x = 51.4 mm. In practice the spacing was rather larger, and breaks on either side were independent and did not occur along the whole length of the reinforcement. The differences between the simple theoretical treatment and observations are most probably due to the variation of σ_C along the bar (caused by changes in fibre packing) and changes in shear strength. The compressive stress is given by equation (5). Assuming that the modulus and strength of the composite are equal to the fibre volume fraction times the appropriate fibre property equation (5) indicates that the induced compressive stress is exceeded by the material strength by 27% at a fibre volume fraction of 0.5. Thus to avoid failure in the reinforcing strips applied to the alloy bar it should be sufficient to increase the fibre fraction to 0.5.

3.3 Delamination

Peretz[2] has attempted to calculate the interface stresses on a two-component beam and shown that within 5% or so of the ends the stress rises rapidly, the value increasing with increasing shear modulus of the adhesive layer. His solution is complex and an alternative approach based on shear lag analysis is considered here. Following the treatment given in (3) we consider two layers of carbon fibre composite, each of thickness a, attached to either side of a piece of aluminium alloy (the matrix in (3)). Stresses produced in the two materials by straining are different because of the different elastic moduli and consequently shear stresses are produced on all planes parallel to the long axis of the bar. The compressive stress in the composite σ_C' is given by

$$\sigma_C' = E_C\, e\left[1 - \frac{\cosh\beta(^1/2 - x)}{\cosh\beta 1/2}\right] \tag{7}$$

where e is the overall, matrix, strain and 1 the length of the bar.

Following the approach in (3) but allowing for the different geometry of the bar we find that

$$\beta = \sqrt{\frac{G_A}{E_C\, ah}} \tag{8}$$

where h is the thickness and G_A the shear modulus of the aluminium alloy.

The interface shear stress, τ, is given by

$$\tau = \sqrt{\frac{a}{h}\frac{G_A}{E_C}}\, E_C\,(\alpha_A - \alpha_C)\,\Delta T\;\frac{\sinh\beta(^{l}/2 - x)}{\cosh\beta\, l/2} \qquad (9)$$

since $e = (\alpha_A - \alpha_C)\,\Delta T$.

This equation indicates that τ increases with an increase in the ratio $\frac{a}{h}$, G_A, E_C, $(\alpha_A - \alpha_C)$, and ΔT. It should be noted that increasing the fibre loading to lessen the occurrence of buckling failure in the composite results in an increase in E_C and hence a greater likelihood of delamination. Using the values previously taken for the various constants, taking $x = 0$, $a = 3$ mm, $G_A = 27$ GPa, and approximating $\frac{\sinh\beta\, l/2}{\cosh\beta\, l/2}$ to unity for large values of $\beta l/2$, equation (9) gives $\tau = 52.3$ MPa. The metal composite interface strength was not determined experimentally but since 52.3 MPa is greater than the interlaminar shear strength of the composite debonding failure at the ends of the bars is very likely.

4. Conclusion

Two 7 m long aluminium alloy bars stiffened with carbon fibre composite have been produced. A certain amount of compression failure and end delamination occurred in the composite when the hybrid beam cooled down but this could be repaired. The bars have been used successfully for some months now as single turn primary conductors passing through the window area in the two cores of a Scott connected transformer.

The causes of the compression damage and delamination have been accounted for in terms of simple composite models.

Acknowledgements

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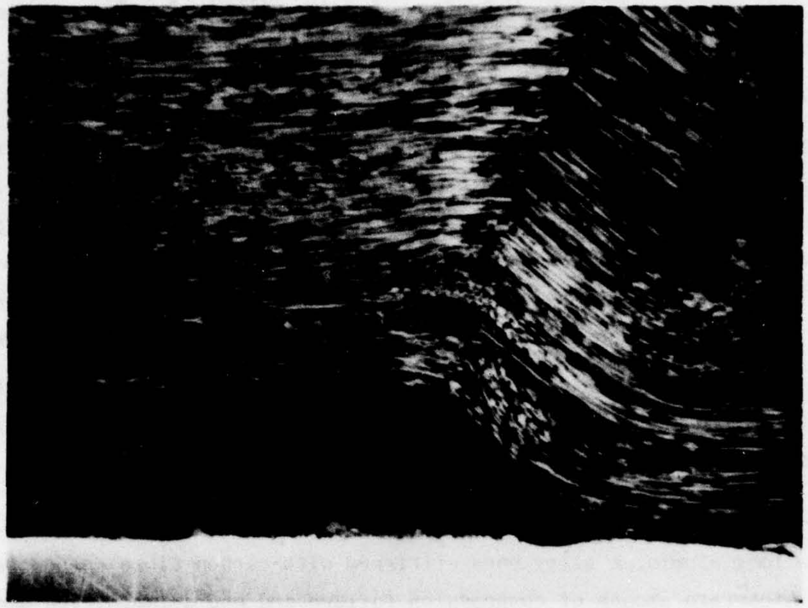
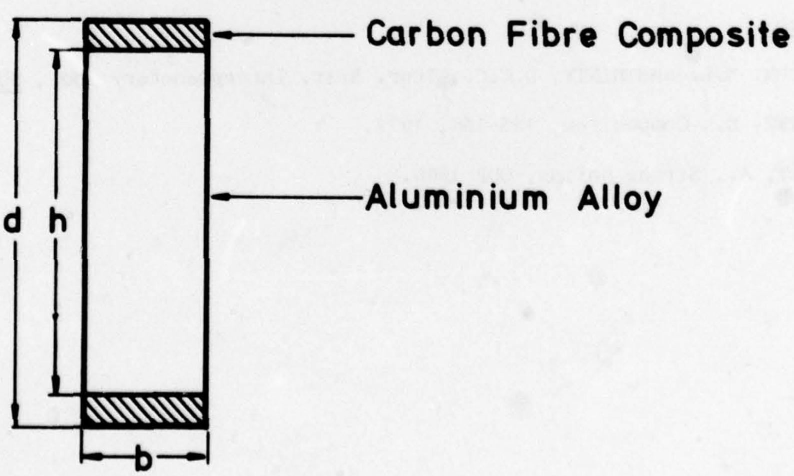


AERE - R.9235 Fig. 1

Compression failure in CFRP. The black area is a void due to debonding. The light area at the bottom is part of the aluminium.



AERE - R.9235 Fig. 2

Cross section of carbon fibre composite reinforced aluminium alloy bar